# MACHINE LEARNING FOR INFORMATION MANAGEMENT

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# ABSTRACT

This paper discusses machine learning in the context of information management. The core idea is that of a compiler system that can hold a conversation with a user in English about his specific domain of interest, subsequently retrieve and display information conveyed by the user, and apply various types of external software systems to solve user problems.

The specific learning problem discussed is how to enable computer systems to acquire information about domains with which they are unfamiliar from people who are expert in those domains, but have little or no training in computer science. The information to be acquired is that needed to support question-answering or fact retrieval tasks, and the type of learning to be employed is learning by being told. Reflecting the intimate connection between language and reasning, this paper is largely concerned with the problems of learning concepts and language simultaneously.

# I OVERVIEW

## A. Learning for Information Management

This paper discusses machine-learning aspects of a project whose broad goal is to create computer systems that can aid users in managing information. The specific learning problem discussed is how to enable computer systems to acquire information about domains with which they are unfamiliar from people who are experts in those domains, but have little or no training in computer science. The information to be acquired is that needed to support question-answering or fact retrieval tasks, and the type of learning to be employed is learning by being told.

## B. The KLAUS Concept

Our interest in knowledge acquisition is motivated by the desire to create computer systems that can aid users in managing information. The core idea of what we call a KLAUS* system is that of a machine that can hold a conversation with a user in English about his specific domain of interest, subsequently retrieve and display information conveyed by the user, and apply various types of external software systems to solve user problems. Such software would include data base management systems, report generators, planners, simulators, and statistical packages.

Interactive dialogues in natural language appear to be a convenient means for obtaining most of the application-specific knowledge needed by intelligent systems for information management. But systems that acquire knowledge about new domains through natural-language dialogues must possess some very special capabilities.

KLAUS systems must support interactive, mixed-initiative dialogues. Because a user may provide new knowledge in an incremental and incomplete manner, the system must keep track of what it has already been told, so that it can deduce the existence of missing information

* "KLAUS" stands for Knowledge-Learning and -Using Systems.

and explicitly ask the user to supply it. Moreover, it must carefully distinguish what it does not know from what it knows to be false.

A primary requirement of a KLAUS system is that it be capable of simultaneously learning both new concepts and the linguistic constructions used to express them. KLAUS systems must acquire domain-specific language expertise, not only to understand natural-language statements formulated by the user about his domain, but also for generating natural-language responses to user requests.

The intimate connection between language and reasoning is reflected in the need to acquire concepts and language simultaneously. This poses a great challenge in the task of creating KLAUS systems. Thus, this paper is largely concerned with the problems of learning concepts and language simultaneously.

## C. Research Problems for KLAUS Systems

Before systems can be created that are capable of learning about new domains through interactive dialogues in English, several fundamental research problems must be resolved:

* A powerful natural-language processing capability is required. Although much progress has been made in recent years, previous work has presupposed a complete knowledge base. Knowledge acquisition dialogues require numerous adaptations and extensions to the technology.

* A structure for lexical entries must be specified so that the system can acquire new lexical information. Because such information constitutes a key link between surface linguistic form and underlying meaning, structural specification is a challenging task for certain categories of words, particularly verbs.

* The linguistic constructions that people use in introducing new concepts must be identified and analyzed, so they can be interpreted correctly by the natural-language processing system. Such constructions range from simple syntactic patterns to complex analogies.

* Seed concepts and seed vocabulary must be identified for inclusion in a core system. It is not obvious which words and concepts would be most useful in helping users describe new domains.

* A flexible scheme of knowledge representation is necessary. Such a representation must have general expressive power, since it may be applied to diverse domains and must support the addition of new information. It should include inherent features that can aid in organizing knowledge and supporting incremental acquisition.

* An efficient problem-solving capability is needed to answer questions and draw inferences for integrating newly acquired information. This capability must be based on general principles, because no application-specific problem-solving procedures will be included in the system. (How to learn application-specific problem-solving procedures is a separate and interesting research question.)

* A methodology is needed for integrating new concepts into the system's knowledge base. Because users will often provide only partial descriptions of new concepts, methods must be devised for ascertaining what additional facts should be sought from the user to ensure proper linkage between the new concepts and those previously acquired.

* A set of readily understandable questions is needed for eliciting information from the user. The length and number of questions should be kept to a minimum, so as not to impose an excessive burden on users.

* Facilities must be provided for allowing a user to change his mind about what he has told the system. That is, users should be able to instruct the system to modify, revise or refute information it has been told previously.

* Means are required for detecting and dealing with inconsistent data.

These problems must be dealt with in an integrated manner, balancing the requirements of one facet of the system against those of other facets. Our initial attempts to cope with this complex web of issues are described below.

## D. Other Learning Systems

Our application of the technique called "learning-by-being-told" to collect and organize relatively large aggregations of individual facts for use in question-answering tasks stands apart from two other major approaches in knowledge acquisition research. One of these involves the acquisition of rules for judgmental reasoning, as exemplified by the work of Davis [1] and Dietterich and Michalski [2]. In this paradigm, knowledge is viewed not so much as a collection of facts, but as a set of rules that in their aggregate comprise an algorithm for making some type of decision. The other approach explores learning by example and learning by analogy. This latter notion is the basis of much other research on learning, such as that of Winston [19] and Mitchell [12].

## II TECHNICAL APPROACH: EXPERIMENTS WITH THE KLAUS CONCEPT

We have recently developed and tested a pilot KLAUS, called NANOKLAUS. A sample transcript of interactions with this system is contained in the appendix. Readers are encouraged to glance through this transcript before proceeding with the reading of this text.

The principal components of NANOKLAUS are a natural-language processing module, a formal-deduction module that operates on a data base of well-formed formulas (wffs) in first-order logic, and a number of support procedures that aid in assimiliating knowledge about new subject domains and in maintaining the data base.

### A. Seed Concepts

NANOKLAUS comes preprogrammed with a fixed set of syntactic and semantic rules covering a small subset of English. It also comes with seed concepts and a seed vocabulary, which are to be extended as the the system learns about a new domain. For example, the system comes with a preliminary taxonomy of concepts already defined. This basic set includes such things as PHYSICAL OBJECTS, PERSONS, MEASURES, and the like. NANOKLAUS also has predefined lexical entries for the basic function words of English, as well as of such words as "unit," "kind," and "plural" that are used frequently in articulating definitions of new words and concepts. These seed concepts allow the untrained NANOKLAUS to "understand" inputs such as those of Interactions 3 and 4 of the transcript.

The choice of seed concepts for a system that must bootstrap its entry into new domains is problematical. Most of the concepts we selected for NANOKLAUS are classes of THINGs and RELATIONs. They have been included in the system either simply to avoid forcing users to relate everything to the most general concept (THING), or because they have a special status in English. For example, because pronominal usage depends partially on gender, the class MALE is defined and associated with the pronoun "he."

It is important not to think of the seed concepts as a set of primitives, in terms of which all other concepts must be defined. Concept acquisition in NANOKLAUS is not based on definitions. Rather, new concepts are introduced by the user and progressively refined by adding more and more facts connecting the new concept to other concepts. Each new fact acts as a constraint that the concepts it mentions must satisfy. Thus, concept acquisition is a process of pruning away possibilities, rather than building up from primitives. For arguments as to the general unworkability of the latter approach, see [3].

NANOKLAUS uses seven principles of knowledge organization to integrate new knowledge:

(1) There are things.

(2) There are subclasses of things (i.e., things can be classified taxonomically).

(3) There are relations among things.

(4) There are subclasses of relations.

(5) Some relations are functions (i.e., n to 1 maps).

(6) Sometimes a given set of constraints is sufficient to distinguish a unique individual.

(7) Equals are interchangeable.

NANOKLAUS is not programmed to hold explicit conversations about these principles, but rather to utilize them in its internal operations.

## B. NANOKLAUS's Natural-Language Component

The natural-language component of NANOKLAUS is based on LIFER [6] and uses a pragmatic grammar in the style of LADDER [8]. In particular, its grammar consists of a number of highly specific, special-purpose rules for processing various types of sentences.* For example, the grammar may be thought of as including a rule of the form

```
<SENTENCE>  >  <PRESENT>  THE  <KNOWN-COUNT-NOUN>

                     // (DISPLAY <KNOWN-COUNT-NOUN>),
```

which is used to match such inputs as

What are the ships?<br>
Show me the officers.<br>
List the carriers.

The metasymbol <PRESENT> matches the underlined portion of these inputs, "THE" matches "the," and <KNOWN-COUNT-NOUN> matches the last word in each of the examples. (Count nouns refer to discrete objects that can be counted, such as ships and ports. NANOKLAUS does not deal with mass nouns, e.g., "steel" and "water.")

Whenever a sentence is found that matches this pattern, the function DISPLAY is called with the value of <KNOWN-COUNT-NOUN>. This function thereupon retrieves from the data base and displays to the user all currently known instances of objects that might be referred to by the <KNOWN-COUNT-NOUN>.

Although most of the linguistic processing performed by the system follows fairly standard practice, the pragmatic grammar is distinguished by its explicit identification of a number of syntactic structures used principally to define new concepts. As an oversimplified example, NANOKLAUS might be thought of as looking for the syntactic pattern

---

* The rules used by NANOKLAUS are much more linguistically motivated than those used in LADDER. In our discussion, we have suppressed the complexity of the rules and response functions actually used, so as to characterize the essence of the methodology more succinctly.

<SENTENCE>  > <A> <NEW-WORD> <BE> <A> <KNOWN-COUNT-NOUN>

to account for such inputs as

A CARRIER IS A SHIP.

The system's definition of the category <NEW-WORD> allows <NEW-WORD> to match any LISP atom (or atom sequence). The syntactic category <KNOWN-COUNT-NOUN> originally contains only count nouns associated with seed concepts, such as "thing," "person," "physical object," and the like.

When one of NANOKLAUS's concept-defining patterns is recognized, an assimilation procedure associated with the pattern is called. This procedure usually adds new facts to the system's set of wffs and generates new entries in its lexicon. The various assimilation procedures also have provisions for interacting with the user/teacher. Response generation is accomplished by means of preprogrammed phrases and templates.

For example, when the routine associated with the last pattern shown above is called, it first makes a new lexical entry in category <KNOWN-COUNT-NOUN> for the atom matched by the <NEW-WORD>. In this case, "CARRIER" becomes a new <KNOWN-COUNT-NOUN>. Then the routine creates a new sort predicate[*] for CARRIER in the system's knowledge base and enters the assertion that "for every x, if x is a CARRIER then x is a SHIP." Finally the routine asks questions of the user to determine relationships between the sorts of objects that are CARRIERs and other sorts of objects that are SHIPS. Interactions 7 and 23 of the transcript illustrate this interaction.

[*] A sort predicate is a one-argument predicate that indicates what kind, class, or sort of thing an object is. For example, CARRIER and SHIP are sort predicates in the formula (ALL X) ((CARRIER X)  > (SHIP X)). We use the word "sort" rather than "class" to avoid the conotation that a sort predicate is associated with a set of objects, which could be extensionally defined.

## C. NANOKLAUS's Knowledge Base and Deduction Component

First-order logic was chosen as the basis for NANOKLAUS's knowledge representation scheme because of its generality and because of the computational soundness and power of problem-solving systems that use it.

### 1. Typical Wffs Used by NANOKLAUS

The introduction of sort predicates mentioned above provides an example of how NANOKLAUS makes use of constructs from first-order logic. Whenever NANOKLAUS learns a new count noun, it creates a new single-place predicate to characterize objects of the associated sort. For example, we have seen that, upon learning the concept of a carrier, NANOKLAUS creates a predicate called "CARRIER" and asserts the fact

(ALL X) ((CARRIER X) > (SHIP X)).

As another example of NANOKLAUS's use of formulas in logic, when NANOKLAUS learns that carriers and submarines are distinct sorts of objects, it effectively asserts the fact

(ALL X) (NOT (AND (CARRIER X) (SUBMARINE X)).

When NANOKLAUS learns of a new individual, such as the JFK (see Interaction 26), it creates a new constant term in the logic system and relates it to one of the sorts, namely

(KITTYHAWK JFK).

Upon learning a new verb, such as "command" (see Interaction 18), NANOKLAUS creates a new predicate with the proper number of argument positions and constrains the domains of those arguments by assertions such as

(ALL X Y) ((COMMAND X Y) > (AND (OFFICER X) (SHIP Y))).

Most of the assertions made by a user are translated into propositions in a straightforward manner. Eg., "Brown commands the Saratoga" (see Interaction 43) produces

(COMMAND BROWN SARATOGA).

## 2. Consistency

NANOKLAUS checks each new fact as it is asserted to determine whether it is consistent with its previous knowledge. This gives rise to the behavior shown in Interactions 27, 44 and 45 of the transcript. NANOKLAUS currently has no provision for unlearning. Therefore, if a new assertion causes an inconsistency because a previous assertion was not correct, there is no provision for withdrawing the incorrect assertion.

## 3. More Reasons for Using First-Order Logic

The notion of using first-order logic in combination with automatic deduction as the basis of an intelligent system dates back to the very beginning of AI research. Newell and Simon [15] published a paper on The Logical Theorist in 1956, and McCarthy, in his 1959 "Advice Taker" proposal (republished in 1968 in [11]), suggested using such a combination as the basis of a system capable of commonsense reasoning.

Following a vigorous start, work on the use of logic as a basis for AI systems fell on hard times during the 1960s and early 70s after experimentation by Green [4] and by others showed that the computational effort required to solve problems in first-order logic using Robinson's [16] resolution principle grows exponentially with the number of wffs used in the axiomatization of a domain.

However, more recent work, such as that of Hayes [5], Kowalski [9], Moore [13], and Weyhrauch [18], has suggested how control information may be used to increase the efficiency of the deduction process.

But our main motivation for using first-order logic is that KLAUS systems are incremental learning systems and therefore must be capable of dealing with incomplete knowledge. As pointed out by Moore [14],

> Any knowledge representation formalism that is capable of handling the kinds of incomplete information people can understand must at least be able to

Say that something has a certain property without saying which thing has that property:

SOME (X) P(X)

Say that everything in a certain class has a certain property without saying what everything in that class is:

ALL (X) (P(X) -> Q(X)

Say that at least one of two statements is true without saying which statement is true:

P OR Q

Explicitly say that a statement is false, as distinguished from simply not saying that it is true:

NOT(P)

Any representation formalism that has these capabilities will be, at the very least, an extension of classical first-order logic, and any inference system that can deal adequately with these kinds of generalizations will have to have at least the capabilities of an automatic-deduction system.

## D. Acquisition Procedures: Using Dialogue to Aid Assimilation

By and large, it is unreasonable to expect users to volunteer all the information NANOKLAUS needs to assimilate a new concept. In particular, users cannot be expected to know what conclusions NANOKLAUS will draw about a newly taught concept from its previous knowledge, since they know neither the details of its current state of knowledge nor the even more esoteric details of its assimilation procedures. NANOKLAUS must ask the user explicitly for the information it needs. Therefore, whenever a new concept (or word) is presented to NANOKLAUS, a special procedure is called that temporarily assumes control of the dialogue, prompting the user for whatever additional information it may require to assimilate the new concept.

NANOKLAUS must phrase its questions so as to make them readily understandable by people unfamiliar with computers or linguistics. This introduces a number of human-engineering considerations. The acquisition of new verbs offers a cogent illustration of the problem.

English verbs are highly idiosyncratic. Consequently, making proper entries for them in a lexicon is a formidable task. Among other criteria, one must ascertain whether a verb is transitive, whether it can be used in the passive voice, whether its indirect object can become the object of a FOR or TO prepositional phrase, whether it is reflexive or nonreflexive, and how the syntactic cases of its arguments may be "normalized" when the verb appears in different syntactic constructions. NANOKLAUS's users cannot be expected to describe verbs in linguistic terms; therefore, to elicit the same information, the system must ask a series of questions that users can understand . Interactions 18 and 19 in the transcript are typical verb acquisition exchanges. While the dialogue is moderately natural and can be used by a nonlinguist, there is obviously considerable room for improvement in its design.

## E. Some Major Limitations of NANOKLAUS Technology

Many of the major limitations of NANOKLAUS can be seen simply by reading through the transcript and noting that, although English is being used, the conversation is nevertheless highly stylized and artificial. For the most part, NANOKLAUS is limited to learning about very concrete types of objects and their interrelations. It has no capacity to deal with time, process, causality, intent, want, belief, or judgment. This, of course, severely limits its range of application.

Even when considering concrete objects and their interrelations, NANOKLAUS can deal with only highly specific statements. For example, NANOKLAUS has no capacity do deal with analogy, as in

A SOFTBALL IS LIKE A BASEBALL, BUT BIGGER AND SOFTER.

In general, the interpretation of information volunteered by people about new domains may necessitate deep reasoning and require information from other domains. Much of the volunteered information may contain inconsistencies that the user himself has no way (or particular reason) to resolve. The NANOKLAUS system represents a starting point for work on learning-by-being-told; still, it barely scratches the surface of a vast body of difficult problems.

## III MORE TECHNICAL DETAILS

In this section we present additional details about sme of the more interesting aspects of the NANOKLAUS system.

### A. NANOKLAUS's Sort Hierarchy

NANOKLAUS's knowledge representation system uses a many-sorted, first-order logic that combines features from [13] and [7]. The backbone of the system is a treelike data structure reflecting the hierarchy of sorts used by the system (see Figure 1). The data structure maintains information about the immediate ancestors and descendants of each sort, including whether an ancestor is exhausted (spanned) by some or all of its descendants, and whether two or more sibling sorts are mutually exclusive. The sort hierarchy is a "tangled" tree, i.e., any given sort may have multiple ancestors. It is no accident that a sort hierarchy should serve as the primary data structure for an English-based acquisition system. "ISA" hierarchies are used by many natural-language processing systems; it appears that something very similar to a sort hierarchy plays a central role in the way humans organize their knowledge [10].

```
*********************************************************************

                                     THING
                                     ^ ^ ^
                         ............: : :.....................
                         :             :                      :
                         :             :.....                 :
                         :                  :                 :
               PHYSICAL.OBJECTS       LEGAL.PERSONS        MEASURES
                 ^       ^                  ^              ^     ^
                 :       :                  :              :     :
         ........:       :......   .........:              :     :
         :                     :   :                       :     :
        SHIP                  PERSON                   LENGTH    WEIGHT
         ^                   ^  ^ ^ ^
         |           ........:  : : :........
         |           :          : :...      :
      the-jfk        :      ....:    :      :
                     :      :        :      :
                     :      :        :      :
                     :      :        o------o---(mutually exclusive)
(mutually exclusive)-o------o        :      :
                     :      :        :      :
      (exhaustive)   o      o        :      :
                     :      :        :      :
                   MALE   FEMALE   ADULT   INFANT
                   ^           ^   ^          ^
                   |           :   :          |
                   |           :   :          |
                 john          WOMAN        baby-philip
```

Figure 1: Typical Sort Hierarchy

```
*********************************************************************
```

Straightforward utilization of sort information is illustrated throughout the transcript in the appendix, but especially in Interactions 7 to 14 and 25 to 29.

The sort hierarchy is implemented by means of a special-purpose network representation indicating entailments of systems of unary predicates. Facts stored in this representation can be used exactly like the other facts in the fact store, but are organized to support rapid access to sort information--which is used in the language subsystem as well as in the deduction subsystem. Whenever syntactic combinations are proposed, the parser uses sort information to determine if noun phrases are valid arguments of verbs, adjectives, and relational nouns--thus reducing ambiguity. The response generator consults the sort hierarchy when selecting pronouns for anaphoric reference. If a referent is described as a MALE or a FEMALE, the nominative singular pronoun chosen will be "he" or "she," respectively; if not described as either, but known to be a member of the set of PERSONs, the phrase "he or she" will be used, otherwise "it" will be selected. This can be seen in Interactions 71 and 72 in the transcript.

Sort information is also used to assign default sorts to omitted arguments of verbs. For instance, if an assertion is made that a particular officer commands, NANOKLAUS knows from the acquisition dialogue it had with its teacher that the officer commands <u>something</u>, and that that thing must be of sort SHIP (see Interaction 45).

Measures, or dimensioned quantities, occupy a distinguished place in NANOKLAUS's sort hierarchy; MEASUREs are a distinct sort of THINGs, comprised of LENGTHs, WEIGHTs, PRICEs, etc. The user can define additional sorts of measures. He can also define UNITs in which MEASUREs are measured, as well as the conversion factors between different units of the same measure (see Interaction 5). NANOKLAUS can perform conversion when answering questions (compare Assertion 47 and Questions 58 and 59), although its arithmetic capabilities are quite limited.

## B. NANOKLAUS's Verb System

One of NANOKLAUS's strengths is its ability to deal with a large number of syntactic variations in verb usage. For example, facts asserted in active voice may be queried in both active and passive voice. In general, NANOKLAUS translates clauses into internal structures of the form

(VERB-PREDICATE Arg1 Arg2 Arg3),

using information about permissible syntactic patterns in which the clause's verb can occur.

The basic verb patterns handled by NANOKLAUS are summarized in Figure 2. [NANOKLAUS does not handle modal verbs (e.g., "want" and "know"), or verbs with adverbial particles (e.g., "pick up," "preside over"), or sentential objects (e.g., "The captain requested that the ship change course").] The objective of NANOKLAUS's verb acquisition dialogues (Interactions 18 and 19) is primarily to determine which patterns may be used with a new verb. The system does not need to ask about each pattern. For example, if pattern A3 is not used with a given verb, patterns A3D, A3W, P3, P3', and P3D are automatically ruled out.

| Pattern | Arg1<br>(A) | Arg2<br>(B) | Arg3<br>(C) | Sample Sentence of this Pattern |
|---|---|---|---|---|
| A3 | Subj | NP1 | NP2 | A Joe gave B Sue C a-ball. |
| A3D | Subj | NPd | NP | A Joe gave C a-ball to B Sue. |
| A3W | Subj | NP | NPw | A Joe supplied B Sue with C a-ball. |
| P3 | (NPb) | NP | Subj | C a-ball was given B Sue (by A Joe). |
| P3′ | (NPb) | Subj | NP | B Sue was given C a-ball (by A Joe). |
| P3D | (NPb) | NPd | Subj | C a-ball was given to B Sue (by A Joe). |
| A2 | Subj | - | NP | A Joe wrote C a-letter. |
| A2′ | Subj | NP | - | A Joe wrote B Sue. |
| A2D | Subj | NPd | - | A Joe wrote to B Sue. |
| P2 | (NPb) | - | Subj | C a-letter was written (by A Joe). |
| P2′ | (NPb) | Subj | - | B Sue was written (by A Joe). |
| A1 | Subj | - | - | A Joe wrote. |
| A1′ | - | - | Subj | C a-vase broke.<br>(from A2 of "A Joe broke C a-vase.) |

Pattern names indicate active (A) or passive (P) voice, the number of top-level noun phrases occurring in the sentence, and (in some cases) an indication of a dative noun phrase (D) moved into a "to" or "for" prepositional phrase, or an indication of a "with" (W) prepositional phrase.

Notation:

| | |
|---|---|
| Subj | the surface subject of the sentence. |
| NP1 | the first unmarked <NP> in the verb phrase. |
| NP2 | the second unmarked <NP> in the verb phrase. |
| NP | the only unmarked <NP> in the verb phrase. |
| NPb | <NP> marked by the preposition "by." May be omitted. |
| NPw | <NP> marked by the preposition "with." (not instrumental) |
| NPd | <NP> marked by either "to" or "for." (dative) |

Figure 2: Verb Usage Patterns

To appreciate the range of variation in English verbs, consider the following sentences, each of which describes a situation using a ditransitive verb construction (the A3 pattern of Figure 2). The symbol '*' marks ungrammatical sentences; '?' marks sentences whose grammaticality is questionable.

A3

John cooked Mary the fish.

? John supplied the school the books.

* John ran Mary the machine.

(I.e., John ran it for Mary.)

John served Mary the fish.

John caught Mary the fish.

The following sentence sets are variations of the above, using the same verbs but in different syntactic patterns. In each set the same pattern is used throughout. Notice that not all verbs can be used grammatically in each pattern and that, moreover, some patterns act to describe a different situation from the ones described above (marked by '-').

A3w

- John cooked Mary with the fish.

John supplied the school with the books.

- John ran Mary with the machine.

- John served Mary with the fish.

- John caught Mary with the fish.

A3d (for)

John cooked the fish for Mary.

? John supplied the books for the school.

John ran the machine for Mary.

- John served the fish for Mary.

John caught the fish for Mary.

A3d (to)

* John cooked the fish to Mary.

John supplied the books to the school.

* John ran the machine to Mary.

John served the fish to Mary.

* John caught the fish to Mary.

A2'

- John cooked Mary.

John supplied the school.

- John ran Mary.

John served Mary.

- John caught Mary.

A1

John cooked.

? John supplied.

- John ran.

```
           John served.
         ? John caught.

A1'        The fish cooked.
---      * The books supplied.
           The machine ran.
         * The fish served.
         * The fish caught.
```

There are two principal steps in the translation of a clause expressed in English into a proposition in first-order logic. First, syntactic analysis recognizes which of the various verb patterns is being used. Then syntactic cases (such as SUBJ and NP1) are mapped into argument positions for the predicate associated with the verb sense. For example,

JOHN GAVE SAM FIDO

is in the A3 pattern. According to the table of Figure 1, its SUBJect JOHN is therefore mapped to Arg1, its indirect object (or NP1) to Arg2, and its direct object (or NP2) to Arg3. The end result is the proposition

(GAVE JOHN SAM FIDO)

The related sentence

FIDO WAS GIVEN TO SAM

is in the P3D pattern, so the subject is mapped to Arg3 and the dative SAM to Arg2, resulting in (GAVE -- SAM FIDO), which in turn is converted into (EXIST X)(GAVE X SAM FIDO).

## C. Relating KLAUS Systems to Conventional DBMSs

In several ways, basic KLAUS systems such as NANOKLAUS are similar to conventional DBMSs (data-base-management systems) in that they are intended to file, sort, selectively recall, and display data in various formats. However, DBMSs are systems for dealing with data structures through a formal command/query language, whereas a KLAUS is a system for learning and manipulating concepts through interactions in English.

Furthermore, conventional DBMSs store only single-fact sentences, such as

THE KENNEDY IS OWNED BY THE U.S.

Facts involving logical connectives, such as "OR" in

THE KENNEDY IS EITHER IN PORT _OR_ AT SEA,

or involving quantification, such as

_ALL_ CARRIERS CARRY DOCTORS,

are not ground literals and cannot be represented explicitly in a conventional DBMS. They can, however, be represented, discussed and reasoned about in the first-order logic supporting a KLAUS.*

## IV CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

NANOKLAUS is best described as a fragile, proof-of-concept system that was built to establish the feasibility of achieving the broader KLAUS goals. The natural-language research group at SRI International is now implementing a more sophisticated KLAUS, called MICROKLAUS. MICROKLAUS will cover a broader range of English constructions by replacing NANOKLAUS's LIFER-based pragmatic grammar with Jane Robinson's [17] DIAGRAM grammar. MICROKLAUS will also feature a more efficient deduction system than the one used by its predecessor.

Our work on the subject of knowledge acquisition has only recently begun and there are many capabilities that we have yet to address. For example, NANOKLAUS has no provision for learning by analogy, acquiring or reasoning about the internal structures of processes, dealing with causality, handling mass terms, allowing users to change their minds

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* As of July, 1981, universal quantification was operational in the MICROKLAUS system, and both universal quantification and disjunction were operational in its deduction and representation components.

about previously asserted "facts," or dealing with multiple senses of words.

The KLAUS project is not limited to the study of knowledge acquisition, but is intended to provide technology for a system that combines a knowledge of how to use various software packages with an ability to learn facts about new domains. It is intended that an advanced KLAUS system act as a kind of broker between multiple external agents, one of whom happens to be the user.

The following deceptively simple hypothetical dialogue illustrates the value and the basic characteristics of such an advanced KLAUS:

1. User: > DO I HAVE NEW MAIL?

2. KLAUS: You have one message
   FROM: HENDRIX
   SUBJECT: NSF funds have been cut by Congress
   Do you want to read it now?

3. User: > YES

4. KLAUS: (Presents message about funding cuts at NSF.)

5. User: > WHO ARE THE PROJECT LEADERS ON OUR NSF GRANTS?

6. KLAUS: The following table presents the PIs of NSF projects in the AI Center.

| PI | PROJECT |
|---|---|
| Fischler | 1202 |
| Grosz | 6194 |
| Robinson | 7483 |
| Waldinger | 7409 |
| Witkin | 8682 |

7. User: > FORWARD THE MESSAGE TO THEM.

In this dialogue, the user first asks about his mail (Utterance 1).* Then the user says he wants to read his message, whereupon KLAUS

* This dialogue does not require KLAUS to understand the title or body of the message; however, KLAUS must understand that there was a message and that it was from Hendrix.

displays it. It is about funding cuts at NSF. The user decides to find out who the project leaders of the relevant projects are, so he asks Question 5. Subsequently, in Request 7, he asks that the message be forwarded to these leaders.

Most of the capabilities required for this dialogue can be found in existing systems. However, no system yet built is able to support the entire interaction as shown, because all systems to date lack a controlling and coordinating top level that would enable a single system to

* Interact with the user in natural language.
* Decide which of several subsystems should be invoked to meet the user's needs.
* Automatically create and execute the calling sequences to invoke those subsystems.
* Maintain a dialogue context with the user that reflects and integrates the various local contexts that have been established by and for the use of subsystems.

In other words, present systems lack a crucial level of awareness of the interrelationships and potential interactions of the various software packages, the user, and the domain of application. In short, processing the sample dialogue requires knowledge of the domain of application, and of computer programs, as well as knowledge of the way these pieces fit together in a larger framework. How to acquire, represent, and apply such knowledge in a computer-based system are major problems for future research.

## ACKNOWLEDGMENTS

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# APPENDIX

## Training NANOKLAUS About Aircraft Carriers

What follows is a transcript of a dialogue with the NANOKLAUS system. The consecutive numbers at the left of some lines are NANOKLAUS prompts; the sentences on those lines are typed by the user. Because subsequent utterances by NANOKLAUS and the user are clearly distinguishable, they are not specially marked. Some of the interaction has been deleted to shorten the transcript. Sentences in braces are descriptive annotations.

```
@nanoklaus
 Welcome to Nanoklaus !
 Just say 'Help' if you need help.

 1_what do you know about?                      {The user asks NANOKLAUS
                                                 what classes of things
                                                 have been described to it.}
 I know about PHYSICAL OBJECTS, PEOPLE, MEN, WOMEN, MEASURES, and
 THINGS (of course).
 2_A length is a measure                        {The user defines LENGTH.}
 You're saying that anything that is a LENGTH is also a MEASURE.
 Ok, now I understand LENGTH.
 3_A foot is a unit of length                   {The user defines FOOT.}
 FOOTS are the first units of LENGTH you've defined.
 Now I understand FOOT.
 4_The plural of foot is feet
 FEET - got it. Thanks.
 5_A meter is a unit of length
 How is it related to FOOT? There are 3.3 feet in a meter
                                        {Whenever an additional unit of a
                                        measure is defined, NANOKLAUS
                                        requests the factor for conversion
                                        to one of the previously defined
                                        units.}
 Now I understand METER.
 6_A physical object has a length       {The user gives the domain over
                                         which an attribute named LENGTH
                                         is defined, and implicitly
                                         indicates that the value of this
                                         attribute must be an element of
                                         the set of lengths, defined in (2).}
 So PHYSICAL OBJECTS have LENGTHS.
 Must a PHYSICAL OBJECT have exactly one LENGTH?  yes
                                       {NANOKLAUS determines that the
                                        relationship between physical objects
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                                                 and lengths is functional.}
7_A ship is a physical object
You're saying that anything that is a SHIP is also a PHYSICAL OBJECT.
Is PERSON a proper subclass of SHIP?  no        {When a new subset of an
                                                  existing set is created,
                                                  NANOKLAUS queries the user
                                                  to determine how it relates
                                                  to that set, as well as to
                                                  other previously defined
                                                  subsets of that set.}
Is PERSON necessarily composed of entirely different members from
SHIP?  yes
Do PERSON and SHIP span the set of all PHYSICAL OBJECTS?  no
Ok, now I understand SHIP.
8_A ship is a unit                        {Sorts may be subsets of more than
                                           one set.}
You're saying that anything that is a SHIP is also an UNIT.
What is an UNIT?  a thing                 {NANOKLAUS always wants to know
                                           how the set and superset relate to
                                           the existing taxonomy (the taxonomy
                                           is always a connected graph). Note
                                           that it generated the incorrect
                                           indefinite article in the question,
                                           but see Interaction 9 below.}
You're saying that anything that is an UNIT is also a THING.
Which of the following, if any, are proper subclasses of UNIT:
PHYSICAL OBJECT or MEASURE?  neither of them
Which of the following classes, if any, could never have any members
in common with UNIT:
PHYSICAL OBJECT or MEASURE ?  neither of them
Ok, now I understand UNIT.
Ok, now I understand SHIP.
9_A unit                                  {The user corrects NANOKLAUS's English.}
OK, A UNIT
10_A submarine is a ship                  {Feedback from NANOKLAUS, such as
11_A destroyer is a ship                   seen in Interaction 8, is omitted
12_A carrier is a ship                     for the sake of brevity.}
13_A Kittyhawk is a carrier
14_A Forrestal is a carrier
You're saying that anything that is a KITTYHAWK is also a CARRIER.
Is KITTYHAWK a proper subclass of FORRESTAL?  no
Is KITTYHAWK necessarily composed of entirely different
members from FORRESTAL?  yes
Do KITTYHAWK and FORRESTAL span the set of all CARRIERS?  no
Ok, now I understand KITTYHAWK.
15_A Hermes is a carrier
16_A task group is a unit
17_An officer is a person
18_An officer can command a ship                {Here the verb COMMAND is
Give the  -ed  and  -en  forms of COMMAND        defined as mapping into
(for example, for GO:  WENT GONE):               a predicate over
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commanded commanded                             (officer, ship) pairs.}
If an OFFICER can COMMAND a SHIP something , type in  the most general
description of that thing, otherwise type <carriage return>
                                               {NANOKLAUS tried to determine
                                                if COMMAND doesn't in fact
                                                take a third argument.}
If an OFFICER can COMMAND something a SHIP, then please type in
the most general description of that thing,
otherwise type <carriage return>
If an OFFICER can COMMAND something to a SHIP, then please type in
the most general description of that thing, otherwise <carriage return>
                                               {In this context, "to"
                                                marks an indirect object,
                                                not the destination of a
                                                verb of motion.}
If an OFFICER can COMMAND a SHIP to something , then please type in
the most general description of that thing, otherwise <carriage return>
Can a SHIP be COMMANDED by an OFFICER ?  yes
                                               {NANOKLAUS acquires informa-
                                                tion enabling it to map
                                                into a canonical predicate
                                                calculus form from passive
                                                occurrences of the verb and
                                                occurrences in which some of
                                                the noun phrases are
                                                omitted.}
Can a SHIP COMMAND ?  no
Can an OFFICER COMMAND ?  yes
19_An officer can assign a task group a unit   {Another example, this time
Give the  -ed  and  -en  forms of ASSIGN        a ditransitive verb.}
(for example, for GO:  WENT GONE):
assigned assigned
Can an OFFICER ASSIGN a UNIT TO a TASK GROUP ?  yes
Could a UNIT be ASSIGNED a TASK GROUP by an OFFICER ?  yes
Can an OFFICER ASSIGN a UNIT with a TASK GROUP ?  no
Can an OFFICER ASSIGN a TASK GROUP ?  no
Can an OFFICER ASSIGN ?  yes
20_Some ships can be nuclear           {NANOKLAUS is taught an adjective,
                                        which it maps into a unary predicate
                                        whose domain is ships.}
You're saying that at least one SHIP could be nuclear.
21_A nationality is a thing
22_A ship has a nationality
So SHIPS have NATIONALITIES.
Must a SHIP have exactly one NATIONALITY?  yes
23_A rank is a thing
You're saying that anything that is a RANK is also a THING.
Which of the following, if any, are proper subclasses of RANK:
PHYSICAL OBJECT, LEGAL PERSON, MEASURE, UNIT, or NATIONALITY?  none of them
Which of the following classes, if any, could never have any members
in common with RANK:
```

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PHYSICAL OBJECT, LEGAL PERSON, MEASURE, UNIT, or NATIONALITY ?  all of them
Ok, now I understand RANK.
24_An officer has a rank
25_A carrier has a doctor who is a person       {Here the attribute named
So CARRIERS have PEOPLE for DOCTORS.             DOCTOR takes values that
Must a CARRIER have exactly one DOCTOR?  no      must be members of the set
                                                 of persons.}
26_The JFK is a Kittyhawk                       {First introduction of an
You're saying that JFK is one instance of a KITTYHAWK.     individual.}
Ok, now I know about JFK.
27_The JFK is a Forrestal
You're saying that JFK is one instance of a FORRESTAL.
Sorry, but JFK is an individual of the following types: KITTYHAWK,
and one of them conflicts with FORRESTAL.
                                         {NANOKLAUS used its knowledge of
                                          subset relationships to discover
                                          and then report an inconsistency
                                          in its user's assertions.}
28_The Saratoga is a Forrestal
29_The Enterprise is a carrier
30_The Bulwark is a Hermes
31_US is a nationality
32_UK is a nationality
33_US is the nationality of the JFK             {Asserts the value of
Proving  (US is the nationality of JFK)         an attribute.  Note that,
Asserting that (US is the nationality of JFK)   instead of blindly entering
                                                the fact in the fact store,
                                                NANOKLAUS first checks as to
                                                whether it already knows
                                                the fact.}
34_The nationality of the Saratoga is US
35_The nationality of the Enterprise is US
36_The nationality of the Bulwark is UK
37_Moffet is an officer
38_Brown is an officer
39_Captain is a rank
40_The rank of Brown is captain
41_Captain is the rank of Moffet
42_The JFK is commanded by Moffet        {Uses verbs to describe an
Proving  (MOFFET commanded JFK)           event or situation.  Note trans-
Asserting that (MOFFET commanded JFK)     formation from passive to active
                                          voice by NANOKLAUS.}
43_Brown commands the Saratoga
Proving  (BROWN commanded SARATOGA)      {NANOKLAUS employs an untensed logic;
Asserting that (BROWN commanded SARATOGA)  its canonical expression of its
                                          knowledge is always past tense.}
44_Moffet commands the JFK.
Proving  (MOFFET commanded JFK)
I already knew that.                     {NANOKLAUS detected that it had
                                          previously been told this,
                                          although in a different voice.}
```

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45_Brown commands.
Proving  (BROWN commanded Some ship)   {NANOKLAUS filled in the omitted
                                        argument and then determined that
                                        it had been told of an event or
                                        situation that could conceivably
                                        have been a description of the
                                        same event or situation.}
Is any one of the following statements true concerning this event:
the SHIP is SARATOGA ?  Yes
46_Brown commands a Forrestal.
Proving  (BROWN commanded Some forrestal)
Is any one of the following statements true concerning this event:
the FORRESTAL is SARATOGA ?  Yes.
47_1072 feet is the length of the JFK
Asserting that (1072 FEET is [equal to] the LENGTH of JFK)
48_The length of the Bulwark is 650 feet
49_ctg18 is a task group
50_ctg36 is a task group.
51_Moffet assigned the Saratoga to ctg36
Proving  (MOFFET assigned CTG36 SARATOGA)
Asserting that (MOFFET assigned CTG36 SARATOGA)
52_The Saratoga was assigned to ctg18 by Brown
Proving  (BROWN assigned CTG18 SARATOGA)
Asserting that (BROWN assigned CTG18 SARATOGA)
53_The Enterprise is a nuclear ship           {Uses a predicate adjective.}
54_What are the ships?                         {The user interrogates
ENTERPRISE, JFK, SARATOGA, AND BULWARK.         NANOKLAUS to verify that it
                                                has assimilated what it
                                       has been told. Note that the user has
                                       not explicitly described any of the
                                       answers as ships.}
55_Who commands the Kittyhawks?
(MOFFET JFK).
56_Who commands the JFK?
MOFFET.
57_Brown commands what?
SARATOGA.
58_What is the length of the JFK?
1072 FEET.
59_How many meters is the length of the JFK?
Proving (Some length is [equal to] the LENGTH of JFK)
324.8485.                              {Using the unit conversion factor.}
60_What is the nationality of the Saratoga?
US.
62_Brown assigned what ships?
Proving  (BROWN assigned Some task group Some ship)
(CTG18 SARATOGA).                     {I.e., Brown assigned CTG18 Saratoga.}
63_Who assigned ships to ctg36?
Proving  (Some officer assigned CTG36 Some ship)
(MOFFET SARATOGA).
64_Who assigned ctg18 the Saratoga?
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Proving  (Some officer assigned CTG18 SARATOGA)
BROWN.
65_Who assigned the Saratoga?
Proving  (Some officer assigned Some task group SARATOGA)
(MOFFET CTG36) and (BROWN CTG18).
66_Which ships are nuclear?
Proving  (Some ship is a nuclear ship)
ENTERPRISE.
67_What do you know about carriers?
US is the nationality of JFK.                    {NANOKLAUS has access to its
US is the nationality of SARATOGA.                fact store indexed by sort,
US is the nationality of ENTERPRISE.              as well as by predicate.
UK is the nationality of BULWARK.                 Here it reports all the
MOFFET commanded JFK.                             atomic facts it has about
                                                  carriers.}
BROWN commanded SARATOGA.
1072 FEET is [equal to] the LENGTH of JFK.
the LENGTH of BULWARK is [equal to] 650 FEET.
MOFFET assigned CTG36 SARATOGA.
BROWN assigned CTG18 SARATOGA.
ENTERPRISE is a nuclear ship.
69_Now describe ship                             {Here it describes all the
SHIP:                                             generic and sort information
A SHIP is a PHYSICAL OBJECT and UNIT.             it has about a given sort.}
Therefore it is also a THING.
SUBMARINES and CARRIERS are SHIPS.
SUBMARINES and CARRIERS cannot have any members in common.
SHIP has the following attributes and types:
NATIONALITY.
SHIPS can be NUCLEAR.
71_Please describe Moffet then describe Brown.     {In reponse to this
                                                    request, NANOKLAUS
                                                    displays all the facts it
                                                    knows about a particular
                                                    individual.}
Moffet is an  officer.  His or her rank is CAPTAIN.  MOFFET
commanded JFK.  MOFFET assigned CTG36 SARATOGA.
Brown is an  officer.  His or her rank is CAPTAIN.  BROWN commanded
SARATOGA.  BROWN assigned CTG18 SARATOGA.
72_Now tell me about Saratoga.
Saratoga is a  forrestal.  Its nationality is US.  BROWN
commanded SARATOGA.  MOFFET assigned CTG36 SARATOGA.  BROWN assigned
CTG18 SARATOGA.
76_Who commands what?
Proving  (Some officer commanded Some ship)
(MOFFET JFK) and (BROWN SARATOGA).
77_good bye
See you later
```

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